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NEUTRINOS AND SUPERNOVAE

Adam Burrows

Departments of Physics and Astronomy
University of Arizona
Tucson, Arizona 85721, U.S.A.

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NEUTRINOS AND SUPERNOVAE

ADAM BURROWS
Departments of Physics and Astronomy,
University of Arizona, Tucson, Arizona 85721, USA

ABSTRACT

For some of us the detection of neutrinos from SN1987A started a clock whose next alarm will sound with the explosion of a galactic supernova. The anticipated abundance of neutrino events from such a blast will dwarf in complexity and detail the sparse event record in IMB and Kamiokande II. Nevertheless, the duration, number, and average neutrino energy of the SN1987A burst were in satisfactory agreement with the theory circa 1980. The neutral current we commemorate here was incorporated into that theory during the seventies. Had it not been, the celebrated accord between theory and neutrino detection would not have obtained. In this paper I present a brief comparison of the basics of supernova neutrino burst theory with and without neutral current effects. However, the bulk of these pages deals with new ideas concerning the role of neutrinos and hydrodynamic instabilities in the mechanism of the supernova explosion itself. Whether as diagnostic or driver, the lowly neutrino plays the crucial role in supernova physics.

1. Lepton Trapping and Neutrino Bursts from Supernovae

The conventional thinking on neutrino bursts from supernovae is detailed in Burrows, Klein, and Gandhi[1] and will not be summarized here in any depth. As a token, I show Figure 1 which depicts the signal fractions in the various interaction channels in the ICARUS detector[2] under the assumption that the modern theory obtains. This pie diagram is representative of the spectrum of responses to a galactic supernova expected in neutrino telescopes now under construction.

In this section, rather than dwell on specific features of the supernova neutrino burst, I focus on a little-known consequence of the existence of the weak neutral current that changes the very character of the supernova neutrino signature. In the sixties and early seventies, the neutrino-matter cross sections that were employed by supernova modelers [3,4] were different from those used today. Since the total energy radiated and the radius of the radiating surface are set (to within factors of three) by basic arguments, there is a natural complementarity between the signal duration and the average emitted neutrino energy. A "low" temperature of 5 MeV perforce implies a "long" duration of seconds. In the first theories, through a combination of slight errors in the neutrino-electron scattering cross section, the neglect at times of the mu- and tau- neutrinos (and anti-neutrinos) and, importantly, the absence of the neutral-current neutrino-nucleon and neutrino-nucleus (Freedman) scattering

processes, neutrino diffusion times out of the residue of collapse were only $\sim 10-100$ milliseconds (compared to $1-10$ seconds today). To radiate a good fraction of the neutron star's binding energy in such a short time required high neutrinosphere temperatures near 30–50 MeV (as compared to 4–5 MeV today). What we saw from SN1987A was nothing like this.

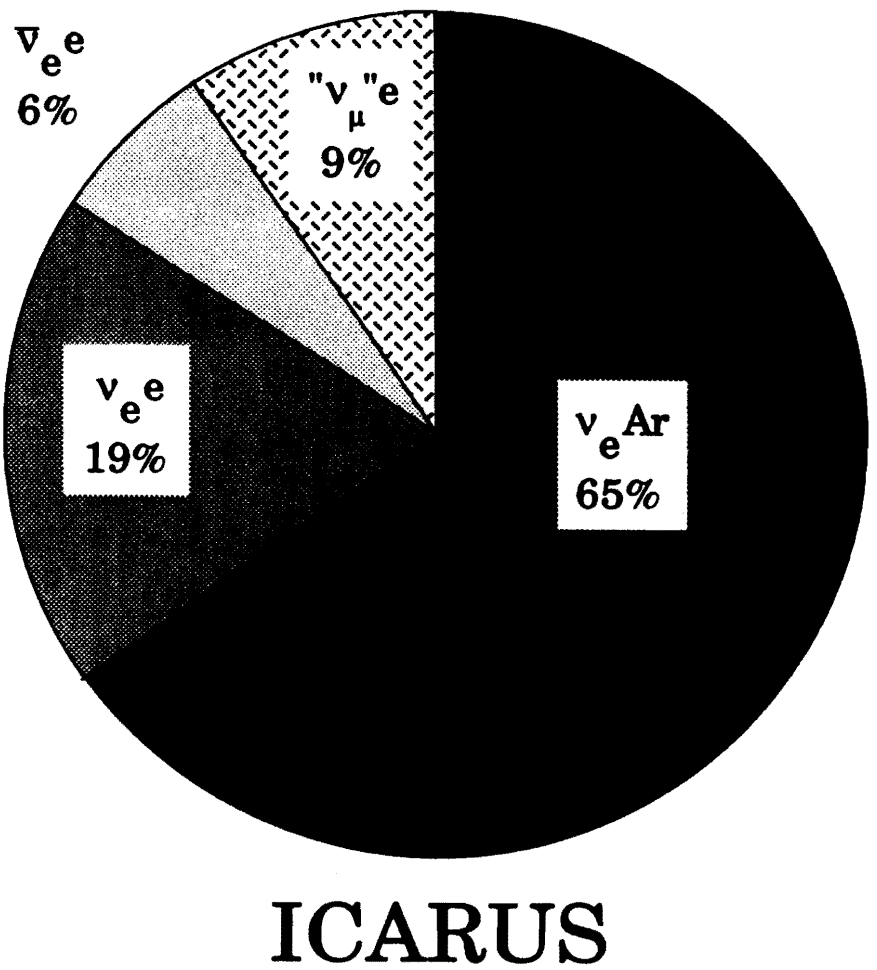

Fig. 1: A pie diagram depicting the fractions of the total neutrino signal theoretically expected via the various interaction channels in the ^{40}Ar of the ICARUS detector.

All else being equal, the inclusion of the neutral current scattering processes naturally results in longer and softer signals. However, there is a more subtle consequence of neutral current processes. During collapse, the energy of electron neutrinos produced by the charged-current electron capture on both free and bound protons increases with the mass density. Since the interaction cross sections are increasing functions of neutrino energy ($\sigma_\nu \propto \epsilon_\nu^2$), the opacity to neutrinos of the collapsing sphere ramps up quickly. After central densities near 10^{11}gm/cm^3 have been achieved, the electron neutrinos are trapped in the flow. Thereafter, electron-neutrino capture on neutrons begins to balance electron capture on protons, a "chemical" equilibrium in the weak interaction is established, and a Fermi sea of trapped and degenerate electron neutrinos grows. As the core approaches nuclear densities, much of the gravitational energy is pumped, not into thermal energy, but into the energy of degenerate leptons and the Fermi energy of the neutrinos climbs. When nuclear densities have been achieved, the "optical" depth to the central neutrinos is a fantastic $\sim 10^{4-5}$ (because of the high matter densities and the high neutrino energies). Hence, the slow diffusive release of neutrinos is in fact a consequence of neutrino trapping on infall. The latter depends crucially on the neutral current. During infall had it not been for the significant cross section via the neutral current of the neutrino-nucleus interaction, the electron neutrinos would have continued to drain lepton number and the electron fraction (Y_e) would have plummeted. At low Y_e's, nuclei drip neutrons and dissolve. Before neutron drip, the pressure is dominated by degenerate, relativistic electrons with an adiabatic index of 4/3. Such a low index means that the pressure can not halt collapse. However, the appearance of the non-relativistic nucleons would have meant that the adiabatic index was $\sim 5/3$. A "5/3's" gas is stable against gravity and collapse would have been halted long before nuclear densities were achieved. A "thermal" bounce at "low" densities near 10^{13}gm/cm^3 and low average neutrino energies (as opposed to a "cold" bounce at nuclear densities and a high average neutrino energy)

TABLE 1

SUPERNOVA NEUTRINO SIGNAL WITH AND WITHOUT NEUTRAL CURRENTS

	W/O N.C.	With N.C.
Δt	100's of milliseconds	$\sim$ 10 seconds
$\langle \epsilon_{\bar{\nu}_e} \rangle$	$\sim 30 - 50$ MeV	$12 - 15$ MeV
$\frac{E(\text{"}\nu_\mu\text{"})}{E(\text{total})}$	$<<1$	$\sim$ 50–70%
Signal at 87A in IMB/KII	$\sim$ 100	$\sim$ 10
ρ_c^0	$\sim 10^{13}$ gm/cm^3	3×10^{14} gm/cm^3
ϵ_{ν_e} (inside)	50–100 MeV	200 MeV

would have resulted in a more rapid loss of neutrinos and energy. This was the theory in the 1960's. Coupled with the copious production of mu- and tau-neutrinos (and anti-neutrinos) (the other consequence of the neutral current), the supernova neutrino signals with and without the neutral current are very different.

Table 1 summarizes the differences between the two theoretical signals. It was something akin to the signal with the neutral current that we "saw" in 1987.

2. The Mechanism of Supernova Explosions

Much of supernova theory is mature and compelling: a Chandrasekhar core collapses dynamically, neutrinos are trapped during infall[5;6], nuclear densities are achieved, the core rebounds and generates a shock wave[7], and this shock wave stalls into accretion[8]. The direct hydrodynamic mechanism has been superseded by the so-called "delayed" mechanism in which neutrino heating behind the stalled shock revives it into explosion[9,10,11,12]. While the direct mechanism was still viable, nuclear physics and the value of the trapped lepton fraction were important components of supernova theory. With its demise, the central focus of supernova theory has shifted to the broader question of the behavior of the simple accretion shock that results.

Supernova theory has been retarded by the reliance on complicated radiation-hydrodynamic codes that run slowly and seldom. The essential elements of the supernova mechanism have been discovered only piecemeal and much has been obscured by minutia. What has been lacking is a simple and quantitative theory of the mechanism of supernova explosions. Recently, Burrows and Goshy[13] (hereafter BG) have derived a critical condition on the neutrino luminosity and the mass accretion flux such that the protoneutron star mantle explodes.

§*2.1. A Critical Condition*

A bounce-shock stalls into accretion within 10–20 milliseconds of its creation. The radius that it achieves (R_s) depends predominantly on the mass accretion flux through it ($\dot{M}$) and the core luminosities of the electron and anti-electron neutrino species, those most strongly coupled to the shocked matter. A quasi steady-state is achieved in which the radius R_s is determined by the equality of $\tau_a = \frac{R_s}{v_1}$ and τ_c, the neutrino cooling time between the neutrinosphere and the shock. R_s is derived using the three equations of hydrodynamics, the neutrino transfer equations, with lepton and energy source and sink terms, and suitable boundary conditions at the shock and the neutrinosphere. The steady-state assumptions allows us to drop the time derivatives and convert the problem into an eigenvalue problem involving ODE's.

To solve this eigenvalue problem BG made many approximations: They used the Newtonian hydro equations, their equation-of-state included only free nucleons, photons, electrons, and positrons, neutrino heating and cooling were assumed to be via the charged-current URCA process on nucleons ($e^- + p \rightleftharpoons n + \nu_e$; $e^+ + n \rightleftharpoons$

$p+\bar{\nu}_e$), the electron-neutrino luminosity (L_{ν_e}), and the spectra of the ν_e's and $\bar{\nu}_e$'s emerging from the core were assumed to be independent of radius, the same, and given by a thermal distribution with a temperature (T_ν) of 4.5 MeV and an η of 0.0. BG set the mass interior to R_s equal to 1.3 $M_\odot$. The shock jump conditions were derived in the strong-shock limit assuming a gamma of 4/3 and the pre-shock densities were given by combining the continuity equation with an infall velocity law, $v = v_{\text{escape}}/\sqrt{2}$. Derived from the hydro equations, the basic ODE's solved were:

$$\frac{dv}{dr} = \frac{\frac{v}{2r}(v_e^2 - 4c^2) + (\gamma_4 - 1)(H - C)}{c^2 - v^2} \tag{1}$$

$$\frac{dT}{dr} = \frac{1}{C_V}\left[\frac{(H-C)}{v}\left(1 - \frac{(\gamma_4 - 1)\chi}{c^2 - v^2}\right) + \chi\frac{2(v^2 - 1/4v_e^2)}{r(c^2 - v^2)}\right] \tag{2}$$

$$\frac{dY_e}{dr} = (P - M)/v \tag{3}$$

$$\dot{M} = -4\pi r^2 \rho v \tag{4}$$

$$L_{\nu_e} = \left(\frac{7}{16}\right) 4\pi R_\nu^2 \sigma T_\nu^4 \ , \tag{5}$$

where $\chi = \frac{T}{\rho}\frac{\partial P}{\partial T}\Big|_V$, C_V is the specific heat at constant volume, $\gamma_4 - 1 = \frac{\partial P}{\partial U}\Big|_V$, c is the speed of sound, $v_e^2 = \frac{2GM}{r}$, H and C are the neutrino heating and cooling rates per mass, respectively, P and M are the electron production and electron-neutrino production rates, respectively, and the other symbols have their standard meanings. For this study, BG used rather simple-minded expressions for H, C, P, and M that were similar to those suggested by Bethe and Wilson[12]:

$$H = 2.03 \times 10^{18} T_\nu^6 D \quad \frac{\text{ergs}}{\text{gm} \cdot \text{s}} \tag{6}$$

$$C = 2.03 \times 10^{18} T^6 \quad \frac{\text{ergs}}{\text{gm} \cdot \text{s}} \tag{7}$$

$$P - M = 0.415(T_\nu^5 D(1 - 2Y_e) - T^5(F_4(\eta_e)Y_e - F_4(-\eta_e)(1 - Y_e))) \quad \frac{\#}{\text{b} \cdot \text{s}}, \tag{8}$$

where D is a dilution factor,

$$D = \frac{1}{2}\left(1 + \left(\frac{R_\nu}{r}\right)^2\right)\left(1 - \sqrt{1 - \left(\frac{R_\nu}{r}\right)^2}\right).$$

For simplicity, in the derivation of eqs. (1) and (2), the "out-of-whackness" term in the first law of thermodynamics was ignored. The luminosity, L_{ν_e}, and T_ν

fix the position of the neutrinosphere, R_ν. For a given R_s, equations (1) – (5) can be solved between R_ν and R_s. BG's prescription for deriving the eigenvalue, R_s, was to find the R_s at a given L_{ν_e} and $\dot{M}$ at which the ν_e "optical" depth from R_ν to infinity was 2/3. This consistency condition is monstrously crude, but encapsulates the essential elements of the correct solution and allowed BG to derive thermodynamic, compositional, and velocity profiles between R_ν and R_s, as well as R_s's, all for given values of L_{ν_e} and $\dot{M}$'s.

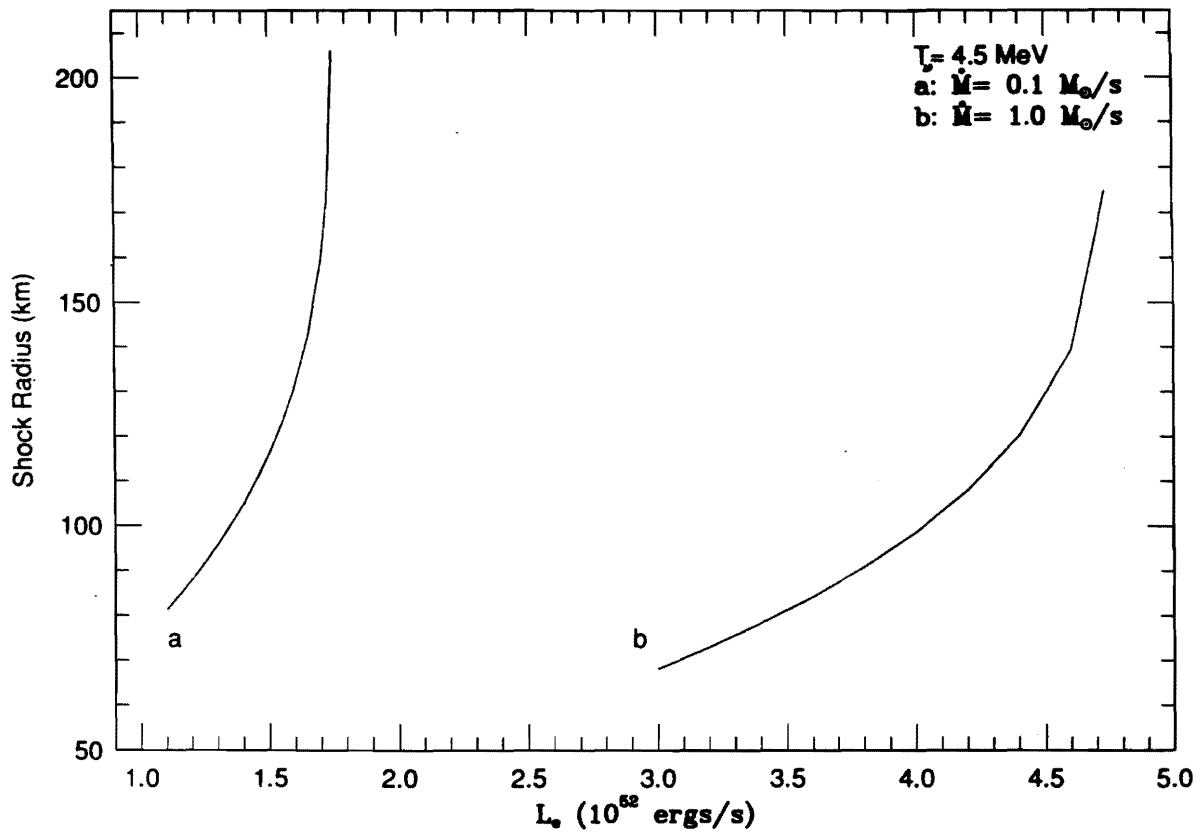

Fig. 2: The shock radius, R_s (in kilometers) versus the electron neutrino luminosity (in $10^{52} ergs/s$) for two different mass accretion rates $\dot{M}$: (a) $\dot{M} = 0.1 M_\odot/s$ and (b) $\dot{M} = 1.0 M_\odot/s$.

For a given $\dot{M}$, M, and T_ν, one can cycle from low to high L_{ν_e}'s to derive the response of the pre-supernova protoneutron star to increasing luminosity. There is always a region with net neutrino heating near the shock, interior to which net neutrino cooling dominates. Net cooling always dominates net heating between R_ν and R_s. The gain radius is at the peak of the entropy profile (cf. $Tv\frac{\partial s}{\partial r} = H - C$). Figure 2 depicts the derived shock radius versus electron neutrino luminosity for two different values of the accretion rate. R_s is a stiff function of the $L_{\nu_e}(\propto L_{\nu_e}^2)$ and decreases with increasing $\dot{M}$ a bit faster than $\frac{1}{\dot{M}}$. R_s for the broad range of parameters is predominantly, but not exclusively, between 80 and 200 kilometers.

The crucial discovery of BG's study was that for a given $\dot{M}$, there is a ***critical*** L_{ν_e}, above which there is no steady-state solution. They identified situations with super-critical luminosities with the supernova explosion. A critical curve of L_{ν_e} vs. $\dot{M}$ can be derived (Figure 3) that separates success from failure. Table 2 summarizes some of the characteristic numbers of the critical solutions. For realistic numbers, R_s does not exceed 210 kilometers. Included in Table 2 is the peak entropy (S_p), which is always less than 21 per baryon per Boltzmann's constant.

TABLE 2
THE CRITICAL QUANTITIES AS A FUNCTION OF
$\dot{M}$ AT $M = 1.3M_\odot$ AND $T_\nu = 4.5$ MeV

$\dot{M}$ ($M_\odot/s$)	R_s (km)	R_ν (km)	L_{ν_e} (10^{52} ergs/s)	S_p
0.07	184.9	25.04	1.451	20.73
0.10	206.1	27.48	1.748	19.65
0.17	180.5	30.92	2.213	17.83
0.30	159.0	34.84	2.810	16.14
0.50	175.3	38.87	3.497	15.29
1.00	174.7	45.21	4.731	14.06
1.50	180.1	49.70	5.718	13.55
3.00	190.8	59.44	8.178	12.92

The solid curve in Figure 3 marked "model trajectory" very roughly traces the path followed by Bruenn's recent simulation[14], but should be interpreted only as representative of a dud. Importantly, Bruenn's R_s settled at $\sim$ 100 kms., below the critical range between $\sim$ 160 kms. and $\sim$ 200 kms. BG predicted that an increase in Bruenn's L_{ν_e} (and $L_{\bar{\nu}_e}$) of only 30%–40% will lead to explosion.

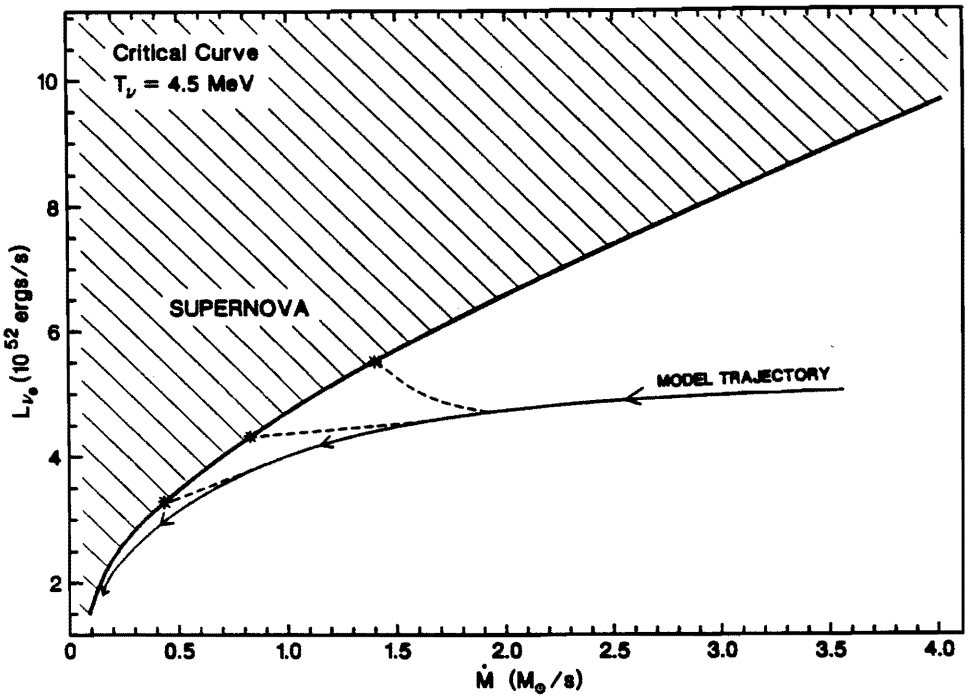

Fig. 3: Depicted in L_{ν_e} (in units of 10^{52} ergs/s) vs. $\dot{M}$ (in units of $M_\odot$/s) space are the critical curve (heavy solid line) of Table 1 (and approximately of eq. (9)) and a representative model trajectory (solid line) of "unsuccessful" core evolution, similar to that found in Bruenn[14]. If the evolution line of a real core crosses the critical curve into the hatched region, a neutrino-driven supernova should begin.

The critical supernova condition that BG discovered is a global stability condition for the entire protoneutron star envelope. Bethe[15], Bethe and Wilson[12], and Bruenn[14] attempted to use local arguments on energy or shock pressure to derive explosion conditions that are not consistent with our results. The protoneutron star is like any star whose oscillation modes and frequencies can be derived by perturbation analysis. There are driving and damping regions. BG conjectured that the imaginary part of the frequency of the fundamental mode of the envelope changes sign from net damping to net driving near the critical configuration (see also Mayle[9]).

A power-law fit to the results of Table 2 and Figure 3 is,

$$\dot{M}_{\rm crit} \sim 1.1 M_\odot/{\rm s} \left(\frac{L_{\nu_e}}{5 \times 10^{52}\,{\rm ergs/s}} \right)^{2.3} \quad . \tag{9}$$

The high power of 2.3 emphasizes the stiff dependence of explosion on the neutrino

luminosity. Improvements in the assumptions and approximations of BG's study, in particular in the neutrino "transport," and different core masses will no doubt change the specific numbers in eq. (9), Table 2, and Figure 3. However, the finiteness of the stable branch and the existence of a critical condition $L_{\nu_e}(L_{\bar{\nu}_e})$ versus $\dot{M}$ seem to be robust new components of supernova theory.

§2.2. *Estimate of the Supernova Energy*

After the critical condition of §2.1 is reached and exceeded, the temperature of the expanding envelope decreases enough to quench neutrino cooling. Thereafter, only neutrino heating is important, the ram pressure at the shock of the infalling matter abates, and there is the expected runaway. The explosion might develop into a transient neutrino-driven wind[16]. Since L_{ν_e} and $L_{\bar{\nu}_e}$ are evolving and it takes a finite time to establish a steady-state, the quasi-steady-state approximation is suspect. Nevertheless, one can solve the steady-state wind equations with neutrino transport for given L_{ν_e}'s and M's and derive wind mass fluxes ($\dot{M}_w$), asymptotic wind velocities (v_w), and, importantly, wind mechanical luminosities at infinity ($L_w = 1/2\dot{M}_w v_w^2$). The latter, integrated over time, should give us an *estimate* of the supernova energy, modulo the binding energy of the ejecta and the thermonuclear component due to explosive nucleosynthesis in the silicon and oxygen zones. Duncan, Shapiro, and Wasserman[17] have already performed a preliminary investigation of winds from neutron stars, motivated by an interest in the photon signatures of such objects. They ignored Y_e – changing processes, but otherwise made many approximations similar to those employed in §2.1 above. Scaling up their results to the supernova regime, BG obtained

$$L_w \sim 4.2 \times 10^{51}\,\mathrm{ergs/s}\left(\frac{L_{\nu_e}}{5 \times 10^{52}\mathrm{ergs/s}}\right)^{3.5}\left(\frac{1.3M_\odot}{M}\right)^2\left(\frac{30\mathrm{km}}{R_\nu}\right)^{4/3} . \qquad (10)$$

The steep dependence on L_{ν_e} in eq. (10) is its most important feature. This high power echoes that in eq. (9) and serves to reemphasize the sensitivity of supernova theory to the driving neutrino luminosities.

As L_{ν_e} decays, M and R_ν change as well. However, if we ignore this and integrate L_w over time, we obtain the total mechanical energy pumped into the supernova after the onset of the blast:

$$E_s \sim 4.2 \times 10^{51}\,\mathrm{ergs}\left(\frac{\tau}{1s}\right)\left(\frac{L_{\nu_e}}{5 \times 10^{52}\mathrm{ergs/s}}\right)^{3.5}\left(\frac{1.3M_\odot}{M}\right)^2\left(\frac{30\mathrm{km}}{R_\nu}\right)^{4/3} , \qquad (11)$$

where we have arbitrarily assumed that L_{ν_e} is constant over a time τ. The work done against gravity in lifting the wind to infinity is already "subtracted" in eq. (11). It is only at very low luminosities that most of the deposited neutrino energy is used against gravity. At the high L_{ν_e}'s relevant during the supernova phase, most of the deposited energy goes into the kinetic energy of the blast.

The total energy radiated (E_ν) during the time τ is $L_{\nu_e}\tau/f$, where f is the ν_e fraction of the total emissions. The ratio $\frac{E_s}{E_\nu}$, which BG calls the efficiency (ε), is proportional to $L_{\nu_e}^{2.5}$. The stiff power means that the same neutrino energy, radiated over a shorter time, is more "efficient" at powering the supernova. The effect of L_{ν_e} on ε is dramatic and implies that a "flash" of neutrinos may be important not only in "igniting" the supernova (eq. 9), but also in powering it[18;19] The 3.5 power in eq. (11) implies that there may easily be a range of supernova energies. A natural mechanism for regulating E_s to be near 1.0×10^{51} ergs is not yet readily apparent. Nevertheless, if we constrain E_s to be equal to 10^{51} ergs, we can derive the τ's and E_ν's required at given L_{ν_e}'s. Some illustrative numbers using eq. (11) are shown in Table 3, conservatively assuming $f = 1/6$. Even a slightly higher L_{ν_e} has *great* leverage in decreasing τ and E_ν, since $\tau \propto E_s/L_{\nu_e}^{3.5}$.

TABLE 3

L_{ν_e}, τ, E_{ν_e}, AND E_ν (TOTAL), ASSUMING $E_s = 10^{51}$ ERGS, $R_\nu = 30$ KM, AND $M = 1.3\,M_\odot$ FOR THE WIND MODEL OF SUPERNOVA ENERGIES

L_{ν_e} (ergs/s)	τ (ms)	E_{ν_e} (ergs)	E_ν (total)
3.0×10^{52}	1434	4.3×10^{52}	2.6×10^{53}
4.0×10^{52}	524	2.1×10^{52}	1.3×10^{53}
5.0×10^{52}	240	1.2×10^{52}	7.2×10^{52}
7.5×10^{52}	57	4.3×10^{51}	2.6×10^{52}

Perhaps the required enhancement in L_{ν_e} is early enough and large enough to keep the bounce shock from stalling[20]. However, it may be impossible to overcome the negative effects of neutrino losses, nuclear dissociation, electron capture, and the prodigious accretion ram during the shock's first 10 milliseconds. Nevertheless, it is conceivable that the shock is reenergized quickly, perhaps within fifty milliseconds. The long delays of 100's of milliseconds to seconds seen in the detailed hydro calculations could be artifacts of the missing neutrino flux and the "long-term" mechanism may be a misnomer. Time is not necessarily required for explosion.

3. Hydrodynamic Instabilities

Recently, there have been indications that Rayleigh-Taylor-like instabilities coeval with the stalling of the shock might advect sufficient heat through the neutrinospheres to enhance L_{ν_e} and $L_{\bar{\nu}_e}$ and provide the flash that the analysis of BG implies might be crucial[16,18,19,21,22,23,24]. In what follows, we summarize the recent results of Burrows & Fryxell[23] (hereafter BF), to which the reader is referred for details.

§3.1. *The Multi-D Code*

The 2-D hydrodynamics code BF employed for their supernova simulations is an extension of the code, *Prometheus*[25], itself an adaptation of the Piecewise–

Parabolic Method (PPM) pioneered by Woodward & Colella[26]. PPM is a non-relativistic, vectorized, explicit, automatically conservative, Eulerian scheme that achieves second-order spatial and temporal accuracy. Fluxes at interfaces are obtained by solving the Riemann shock-tube problem and shocks are resolved to one or two zones. To *Prometheus* was added a vectorized nuclear equation of state that included a representative heavy nucleus, alpha particles, free nucleons, photons, electrons, and positrons, all in nuclear statistical equilibrium[8,21,27]. Neutrino transport was embedded into the code in operator-split fashion. Electron-type (ν_e), anti-electron-type ($\bar{\nu}_e$), and muon-type ("ν_μ" $\equiv \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$) neutrino transport is handled in the "diffusion" approximation out to ten zones beyond the electron-neutrinosphere (at $\tau_{\nu_e} = 2/3$). From this neutrinosphere to infinity, energy and lepton number source and sink terms due to ν_e, $\bar{\nu}_e$, e^-, and e^+ capture on free nucleons were added. The neutrino heating and capture terms assumed that the emerging ν_e's and $\bar{\nu}_e$'s have pinched thermal spectra at their respective decoupling temperatures T_{ν_e} and $T_{\bar{\nu}_e}$ with pinch factors, η, that vary between 0.5 and 3.0, depending on the value of $\eta_{\nu_e}(= \frac{\mu_{\nu_e}}{T})$ at $\tau_{\nu_e} = 2/3$ [28].

The numerical experiment BF reported used 200 radial zones from 20 to 2000 kilometers (from $\sim 0.7 M_\odot$ to $\sim 1.5 M_\odot$), with 120 zones out to 270 kilometers, and 100 equally-spaced angular zones between $-45°$ and $45°$ (half of the first and fourth quadrants). Transport was advanced radially and independently in each angular bin, as if spherical symmetry obtained. So that the influence on the instabilities of the evolution of the Y_e profiles could be properly gauged, lepton transport, with e^- and ν_e capture, was included.

The inner radial boundary was reflecting, the outer radial boundary was a linear extrapolation ("flowout"), and the side boundaries were periodic. The initial model was from Burrows and Lattimer's[8] simulation of the collapse, bounce, and shock stagnation of Weaver, Woosley, and Fuller's[29] $20 M_\odot$ iron core. A random seed perturbation in density of 1% in every zone between 20 and 200 kilometers was applied at the start of the calculation. The total energy and electron lepton luminosities at the inner boundary were set equal to constant values of 2.5×10^{53} ergs/s and 2.0×10^{57} leptons/s, respectively. The boundary energy luminosity divided itself naturally between the various neutrino species as it diffused from 20 kilometers to the neutrinospheres (near 60–80 kilometers).

§3.2. *The Convective Trigger of Explosion*

A major conclusion of the earlier work of Burrows & Fryxell[21] was that, despite the vigor and extent of the overturning motions and the redistribution of the entropy, no explosion results. Since the radius of the stalled shock increased by a mere 10%–15% over its value in the 1-D calculation, they concluded that the convective instability alone does not lead to explosion.

However, when BF turned on the instability by simply going to 2-D, within 20 milliseconds an explosion ensued. By 30 milliseconds, the shock wave was already

at ~350 kilometers. A vigorous, neutrino-heated bubble rose from the inner core and most of the post-shock velocities were positive. The crucial difference between the calculations in 1-D and in 2-D were the latter's rapid overturn between 20 kilometers ($\sim 0.7 M_\odot$) and ~100 kilometers ($\sim 1.1\ M_\odot$). This overturn was driven by unstable lepton and entropy gradients due to shock break-out[30;31]. The ν_e luminosity (L_{ν_e}) was enhanced between 10 and 30 milliseconds from $\sim 4 \times 10^{52}$ ergs/s in the 1-D calculations to between 4 and 8.5×10^{52} ergs/s in the 2-D calculations. During the same time, the $\bar{\nu}_e$ luminosity ($L_{\bar{\nu}_e}$) was boosted from $2 - 4 \times 10^{52}$ ergs/s (1-D) to $2 - 6 \times 10^{52}$ ergs/s (2-D). Heat and leptons were rapidly dredged up from the opaque inner zones and radiated from the neutrinospheres (60–80 kilometers) at an accelerated rate. The factor-of-two enhancements in L_{ν_e} and $L_{\bar{\nu}_e}$ (the convective "flash") are just what is needed to explode the supernova within only tens of milliseconds of stalling[13]. This short time indeed suggests that the neutrino-driven mechanism of supernova explosions needn't be as "long-term" (hundreds of millisconds to seconds) as was originally formulated[32].

4. Conclusions

The general theory of neutrino-driven explosions that I described in §2 is only approximate. Nevertheless, it clearly illustrates the extreme sensitivity of the supernova to the driving luminosities. Higher luminosities with high coupling efficiencies might be achieved by the convective flash discussed in §3. This work by Burrows & Fryxell[22] is suggestive, but not definitive, and must be followed up by independent calculations. Curiously, the viscosity of the protoneutron star mantle might be adequate to affect the convective dynamics on small spatial scales and/or on long time scales. In the calculations of BF, the inertial range (largest scale divided by smallest scale) that can be successfully followed in the code is $\sim$ 100 kilometers/1 kilometers=100. The kinematic viscosity in the mantle ranges between 10^9 and 10^{14} (cgs) and a Reynolds number (Re) of $\sim 10 - 10^3$ is implied. Since $\mathrm{Re}^{3/4}$ is the theoretical inertial range for a Kolmogorov cascade, we see that viscous effects may have to be considered in future simulations (As if merely convecting nuclear matter were not exotic enough!). The total gravitational radiation (GR) output due to these overturning motions (which don't require rotation) may reach $\sim 10^{-9} M_\odot c^2$, producing strains of $\sim 10^{-21}$ at 10 kpc. Such strains may be measurable by a second-generation LIGO. This may make convection the major source of GR from supernovae. Furthermore, a secondary neutrino "burst" due to the convective motions should quickly follow the initial shock break-out burst and would be "visible," if galactic, in Superkamiokande SNO, LVD, MACRO ICARUS, Borexino, or Baksan. Hence, convection could result in diagnostic correlations between the early GR and neutrino signals.

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